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TECHNICAL REPORT

NO. 12407

U.S. ARMY TARADCOM

TRACK PIN INDUCED STRESS

February 1979

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by S. B. CATALANO AND S. T. ALLEN

Tactical Vehicles Function

U.S. ARMY TANK-AUTOMOTIVE
RESEARCH AND DEVELOPMENT COMMAND
Warren, Michigan 48090

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Work reported was for the period 1 October 1977 to 30 September 1978. The objective was twofold: a) To follow track pin residual stress history over the last few processing steps such as core hardening, induction hardening, straightening, grinding, and shot peening; b) To examine the data for evidence of harmful levels or patterns of residual stress that may contribute to track pin failure. A total of 100 track pins were randomly selected from the last seven stages of manufacture at the manufacturer's plant. Residual

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FOREWORD

This work was funded under the In-House Laboratory Independent Research (ILIR) Project/Task No. 1L161101A91A as authorized by TARADCOM.

Appreciation is extended to ILIR project officers Dr. J. Parks and Mr. O. Renius for their comments and suggestions.

Appreciation is offered for the opportunity of working on this timely and challenging project. Acknowledgements are extended to Mr. L. H. Kirkell, President of Blairsville Machine Products Company for the judicious and pleasant manner in which he handled the selection of test track pins for this work at his plant. Acknowledgements are also extended to Mr. C. E. Lynn, process engineer at the Goodyear Tire and Rubber Company for expeditious and careful shot peening of test track pins. Dr. E. Honig and Mr. K. Chesney are thanked for their work performed prior to this study which ultimately inspired performance of this study. They are to be thanked also for their cooperation, suggestions and encouragement.

ABSTRACT

Work reported was for the period 1 October 1977 to 30 September 1978. The objective was twofold: a) To follow track pin residual stress history over the last few processing steps such as core hardening, induction hardening, straightening, grinding, and shot peening; b) To examine the data for evidence of harmful levels or patterns of residual stress that may contribute to track pin failure. A total of 100 track pins were randomly selected from the last seven stages of manufacture at the manufacturer's plant. Residual stress measurements were made in both the longitudinal direction and hoop/transverse direction at 72 spots on each pin. Equipment used was automated x-ray diffraction equipment. Results of the measurements from each pin were tabulated in terms of mean and standard deviation of readings on each pin. Of particular interest to TARADCOM were: 1) Hoop stresses 30K psi less compressive than the longitudinal stresses measured at the same point were generated in the centerless grinding operation, 2) The 30K psi difference in readings is not removed in the stress relief operation, and 3) It is possible to remove the 30K psi difference by shot peening.

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INTRODUCTION AND OBJECTIVE

Residual stresses are induced in components during heat treatment, machining, welding, casting and metal-working processes. These stresses can be of an undesirable nature, concentration, or level due to faulty processing or improper component design, adversely affecting functional performance and durability. Cumulative high dynamic and residual stresses in service may exceed design load limits of the parts. X-ray diffraction is capable of measuring residual stresses nondestructively. Until recently, the method was time-consuming, required expert personnel to operate the equipment, and was limited to small parts or cut sections.

Residual stresses in metals are now easily and quickly measured with recently developed automated x-ray diffraction equipment. Measurements with automated equipment can be made in as short a time as a half minute, whereas previously measurements took as long as 45 minutes per reading.

The x-ray beam size is usually 1/8-inch in diameter or smaller, consequently, it is usually necessary to take readings at many spots rather than just one spot. Often it is desirable to take readings at 100 spots or more. Consequently, time savings using automated equipment can be considerable. These large time savings have stimulated interest in measurement of residual stresses and it has caused TARADCOM to look closer at the effects of residual stresses on component serviceability.

Track pin failures historically have been a problem at TARADCOM. Steps in the right direction have been taken in the past to alleviate this recurring problem. For example, it was found that shot peened track pins last longer under fatigue testing than track pins that were not shot peened. Shot peening induces beneficial compressive residual stresses on the surface of the pin; this acts as a prestress which opposes tensile stresses, thereby allowing the pin to undergo larger applied tensile stresses as imposed in fatigue testing or in vehicular service. To date, track pin problems remain serious enough to warrant intensive study; these problems may be residual stress related or they may be due to other factors. Fatigue testing of track pins having different intensities of shot peening is the subject of proposed future work; residual stress measurement data will be included for each pin tested in that work.

The work reported herein was motivated by the puzzling results of service-type residual stress measurements obtained on track pins as requested on a recurring basis by task force members and more recently by Dr. E. Honig. Shot peening was the final step in manufacturing these pins. Shot peening should impart the same amount of compressive residual stress in all directions on a surface. However, some shot peened track pins submitted for analysis were found to be about 30,000 psi less compressive in the transverse (or hoop) direction than in the longitudinal direction of the pin; some individual hoop stesss readings were actually tensile. This is alarming and provoked the desire to search for the cause leading to this ILIR project. The objectives of this work are:

a. To follow track pin residual stress history over the last few processing steps such as core hardening, induction hardening, straightening, grinding, and shot peening.

b. To examine data for evidence of harmful levels or patterns of residual stress that may contribute to track pin failure.

APPROACH AND EQUIPMENT

A total of 100 track pins were randomly selected for this project from the last seven states of manufacture at the manufacturer's plant, as shown in Figure 1. Ten pins were selected after the core hardening operation, ten after straightening, fifteen after induction hardening, twenty after straightening a second time, twenty after centerless grinding, fifteen after stress relief, and ten after shot peening. In phase I of this work, residual stress measurements were made in both the longitudinal direction and the hoop direction at 72 spots on each pin. In phase II of this work, the pins were returned to the manufacturer; each pin was processed one stage further in the manufacturing process. Residual stress measurements were made in both the longitudinal and hoop directions at the same spots on these pins thereby providing increased data for statistical analysis purposes; in addition, data on these pins will represent data on pins having a known prior residual stress history.

The residual stress measurement technique/method used in the work is the x-ray diffraction method as described in SAE Technical Report No. 182.

In the past, a conventional x-ray diffractometer was used for residual stress analysis work. Figure 2 shows the General Electric Model XRD-3 used in the past for this purpose. It consists of an x-ray tube, a goniometer, an x-ray detector, and an electronic counter and timer. With this type of equipment, three x-ray intensity measurements are made for two different settings of x-ray incidence angle. From the data obtained, the value of residual stress is calculated. The procedure takes about 45 minutes per measurement.

The equipment used in this project was an automatic stress analyzer manufactured by the American Analytical Corporation. This equipment is shown in Figure 3. It is x-ray diffraction equipment automated to measure residual stress using the method described in the SAE Technical Report No. 182. The automated equipment makes use of two x-ray tubes, two goniometers, four x-ray detectors used in pairs (each pair being coupled with a peak-seeking servomechanism), four x-ray activity meters, and electronic circuitry to calculate and display values of residual stress on a strip chart recorder. The strip chart recorder pen oscillates in response to oscillations of the peak-seeking servomechanisms. After about a minute, the pen has drawn enough oscillations for an estimate of the center of oscillation to be determined and the residual stress to be read directly from the strip chart recorder. The accuracy of the automatic stress analyzer is $\pm$ 5,000 psi as compared to $\pm$ 3,000 psi for the conventional x-ray diffractometer. However, the stress analyzer is anywhere from 10 to 100 times faster than the conventional x-ray diffractometer. Because of its greater accuracy, the conventional x-ray diffractometer is used as a check for calibration of the automatic stress analyzer.

On samples, such as weldments, where the residual stress fluctuates rapidly, it is necessary to use a small size x-ray beam. The beam size is controlled by the size of collimator used; the automatic stress analyzer is equipped with three sizes: .030-inch, .045-inch and .060-inch. Either the 30-mil or the 45-mil collimator would be used on weldments. The 60-mil collimators were used in the present study.

Isostress lines were drawn as a pictorial representation of residual stress uniformity/lack of uniformity achieved on the track pins. This was done for only three of the pins studied. The three pins chosen represented a typical pin from the last three processing steps. Automated equipment was used to draw the isostress lines; the equipment consisted of:

1. Analog-to-digital converter to convert the analog data received from the automatic stress analyzer to digital output.

2. Paper tape punch on a teletype with which digital data are punched onto paper tape.

3. Hewlett-Packard 9830 Desk Top Computer (equipped with an x - y plotter) which accepts digital data from paper tape.

4. Computer program for processing the data for x - y plotter use in drawing isostress lines. A listing of the computer program is given in the Appendix.

Results of phase II work on this project duplicated those of phase I so closely that work was suspended after about 70% completion. Graphs, charts, histograms, data sheets and isostress plots for phase II work therefore were not included in this report since they would be a duplication. It should be understood also that the discussion, conclusions, and recommendations reported herein are drawn equally from phase I and phase II work.

RESULTS

The results of the residual stress measurements on each of the 100 track pins were tabulated in terms of mean and standard deviation of readings on each pin. The results obtained are shown in Chart No. 1, a tabulation of range of results obtained on the track pins selected for measurement at the seven stages of manufacture listed in the left hand column. The seven stages are:

1. Core Hardening - Core hardening is a salt bath, quench and temper operation.

2. Straightening - Straightening is required after core hardening because the pins are slightly warped by the core hardening operation. The straightening station is equipped with a dial indicator and a pneumatic press for bending the pin to remove the warp.

3. Induction Hardening - Induction hardening provides the case hardening. It is accomplished by passing the pin through an R.F. induction coil which heats only the outer shell of the pin. The pin is then water quenched as it emerges from the R.F. coil.

4. Straightening - Straightening is required again after the induction hardening step. This is done at the same station used for the first straightening operation.

5. Centerless Grinding - The pins are centerless ground to final size.

6. Stress Relief - In the stress relief operation, 16 skids containing 100 pins/skids are loaded into the stress relief furnace and are held at 350°F for 3 hours, then removed from the furnace to air cool.

7. Shot Peening - Shot peening is similar to sand blasting. However, steel shot is used rather than sand. The shot dimples the surface slightly and creates a beneficial compressive residual stress on the surface.

A mean and standard deviation of readings obtained on each pin was determined for each pin. This was done for the longitudinal stresses and again for the hoop stresses. The data were grouped according to the seven processing steps under study. The highest and lowest means and standard deviations for each group were entered in the chart. In this order, the range of results can be reviewed rather conveniently. The entries are in units of K psi (i.e. 10^3 psi) and are values of residual stress on the surface of the pin only. A positive sign indicates a tensile stress, a negative sign indicates a compressive stress. Instrument accuracy is $\pm$ 5K psi.

As the chart is reviewed, several things should be kept in mind for perspective and assessment purposes:

1. The values of residual stress are expected to change from one processing step to the next reflecting the processing or treatment received.

2. One does not know what values of residual stress to expect as a result of processing steps 1 thru 6 since this has not been studied before. One cannot categorically say the results found are good, bad or indifferent; one can only say that this is what was found and that the purpose of the work was to determine the state of affairs in terms of residual stress after each processing step.

3. One does know in advance that after shot peening (step 7), all of the readings should be compressive. One does not know, however, how highly compressive the readings should be. The track pin drawing calls for the shot peening to be performed according to specification MIL-S-13165B. But MIL-S-13165B specifies shot peen intensity in terms other than residual stress.

4. The failure mode of track pins is known to be tensile. Areas on a final track pin that remain tensile or are only slightly compressive are definitely bad; these areas act as stress risers and promote crack initiation. Characteristic results of the seven groups of track pins tested are as follows:

(a) After core hardening the pins are fairly stress free in both longitudinal and hoop directions. This can be seen from the mean values listed ranging from + 18 to -12. The standard deviations for this group ranged from 2 to 6, indicating a tight distribution of data.

(b) After straightening, longitudinal stresses varied widely and are found to be tensile on one side of the pin and compressive on the other. The large values of standard deviation reflect these large variations. Hoop stresses are not affected much, if at all.

(c) After induction hardening, the pins are difficult to measure and are highly compressive with a wide range of standard deviations. This is true for both the longitudinal and hoop directions.

(d) After straightening again, following induction hardening, residual stresses are found not to have changed appreciably in either the longitudinal or hoop directions.

(e) After centerless grinding, the pins are easy to measure again. More significantly the hoop stresses are now about 30K psi less compressive than the longitudinal stresses; in many instances, individual readings are tensile.

(f) After stress relief compressive residual stresses were lowered and the range of standard deviations were lowered slightly, reflecting a more uniform distribution of residual stresses. However, the hoop stresses are still about 30K psi less compressive than the longitudinal stresses and again in many instances individual readings are tensile.

(g) After shot peening the 30K psi difference between the hoop stresses and longitudinal stresses disappeared and the range of standard deviations diminished. These two observations are indicators of good shot peening.

Charts 2 through 8 display the data obtained in this work in more detail than in Chart 1. Each of these seven charts presents data for one of the seven process steps studied. These data are presented in terms of mean and standard deviations of the readings obtained on each pin.

Individual data sheets obtained from each track pin will not be presented here; however, data sheets for three typical track pins are shown. Data were taken at intersections of imaginary grid lines 1/2 inch x 1/2 inch located centrally on each track pin as shown in Figure 4. Location in the data matrix corresponds to location on the track pin. There are two data sheets for each pin; one is for the longitudinal stresses while the other is for the hoop stresses. Data for track pin #75 (phase I) are shown in Charts 9 and 10. Data for track pin 85 (phase I) are shown in Charts 11 and 12. Data for track pin 95 (phase I) are shown in Charts 13 and 14. In addition to the data sheets for these pins, computer printout of statistical values, computer drawn histograms and computer drawn isostress plots for these data are also given. Charts 15, 16 and 17 show the statistical distributions of data for track pins 75, 85 and 95 (phase I) respectively. Figures 5 (a&b), 6 (a&b) and 7 (a&b) are the histograms for data on track pins 75, 85 and 95 (phase I) respectively. Figures 8 (a&b), 9 (a&b) and 10 a&b) are the isostress plots of the data for track pins 75, 85 and 95 (phase I) respectively. The heavy solid lines in the isostress plots represent the zero level of residual stress. The broken (or dotted) lines represent tensile residual stresses and the light weight solid lines represent compressive residual stresses.

The data sheets, histograms and isostress plots can be used to visualize the presence/absence and location of tensile areas on the track pins. Pin 75 is typical of the pins processed up to and including centerless grinding. Pin 85 is typical of the pins processed up to and including stress relief. Pin 95 is typical of the pins processed up to and including shot peening. The similarity between results on pins 75 and 85 should be noted. Both pins have no tensile readings in the longitudinal direction; both have tensile areas in the hoop direction. Pin 95 has no tensile readings in either direction. Similarly data on pins processed up to but not including centerless grinding have no tensile readings in either direction.

DISCUSSION

It was stated earlier that some shot peened track pins measured prior to this study displayed hoop stresses 30K psi less compressive than the longitudinal stresses measured at the same point and that some of the individual hoop stress readings were actually tensile. It is seen from Chart 1 and in more detailed form from data for pins 75, 85 and 95 that the source of the 30K psi difference was pinpointed in the present study to the centerless grinding step. These data show that:

1. The 30K psi difference is generated in the centerless grinding operation.

2. The 30K psi difference is not removed in the stress relief operation.

3. It is possible to remove the 30K psi difference by shot peening.

This demonstrates that if the shot peening is not adequate, some or all of the 30K psi difference remains and portions of the track pin are tensile in the hoop direction or nearly tensile. This is expected to be a serious factor in track pin failure. Implied also is that the stress relief step is of questionable value. The fact that the 30K psi difference is not removed in the stress relief operation raises questions about the need for the stress relief operation.

CONCLUSION

Some processing steps have large effects on residual stress level; other processing steps have little effect. The various residual stress levels observed after each step and the effects each step has on residual stress level can be seen from Chart 1.

If shot peening is performed properly, the potentially harmful levels of hoop residual stresses (as caused by the centerless grinding step and as left remaining after the stress relief step) are removed.

RECOMMENDATIONS

The value of properly shot peening track pins or other metal parts is stated in the shot peening spec (MIL Spec 13165B) and is quoted verbatim for emphasis: "Shot peening is intended to reduce surface tensile stresses in metal parts which are subjected to repeated applications of complex load patterns such as axles, springs (helical, torsional and leaf), gears, shafting, aircraft alighting gear and structural parts etc., for the purpose of improving resistance to fatigue and stress corrosion cracking." Quality control on shot peening of parts also is governed by this spec; use of almen strips is specified for this purpose. (An almen strip is a flat piece of stress free metal which bends due to imparted residual stresses when it is shot peened only on one side). The degree of bend along the length of the strip is used as an indicator of shot peen intensity as well as for QA purposes.

There is an obvious drawback to this method: It is not a measure of residual stress imparted in the part being shot peened. Rather, it is a measure of how well the shot peening machine is working as measured on a standard part called an almen strip; consequently, it provides little or no information about the part itself. For example, in the case of track track pins, it provides no opportunity for comparison of hoop stresses with longitudinal stresses.

Measurement of residual stress on the part itself with x-ray diffraction does provide this opportunity. The measurement and comparison of longitudinal and hoop stresses was instrumental for this study in locating the source of detrimental levels of residual stress and can be used for in-line (or on a sampling procedure basis) inspection of shot peened track pins to insure that no trace of detrimental residual stress levels are remaining.

Recommended work will have to be done in steps. The first step will be to determine acceptable limits of residual stress on track pins before the shot peening step as well as afterwards. The second step is to implement automated XRD QA on a trial basis at the track pin shot peening facility. After implemented and validated the third step would be to change MIL Spec 13165B to reflect use of automated XRD QA and to proliferate its use to other shot peened parts used in Army tank-automotive equipment.

Further applications that this study lead to and which are recommended for further work are:

1. Improvement of individual processing steps such as centerless grinding. It is to be expected that less abusive grinding will result in a lesser tendency for hoop stresses to be tensile.

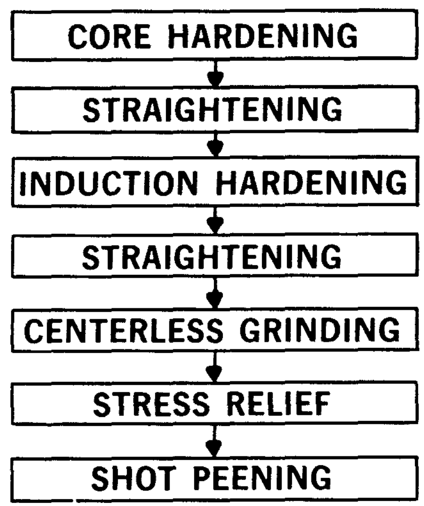
2. Elimination of the stress relief operation in manufacturing processing of track pins.

3. Optimization of the shop peening process for track pins.

It is recommended further that TARADCOM in-house activity in residual stress analysis using automated XRD be expanded. Vast amounts of work in this area have been left undone in the past due to prohibitively time consuming procedure used. Prior to the advent of automated XRD equipment, about five years ago this study would have been absolutely prohibitive and would have been left undone. Similarly other work has been left undone in the past. Now these areas of work represent fertile areas of investigation and work along these lines has a high probability of being productive and profitable.

1. SELECT 100 TRACK PINS AT VARIOUS STAGES OF MANUFACTURE FROM MANUFACTURER'S PLANT.

SELECTION AS FOLLOWS:



10 PINS
10 PINS
15 PINS
20 PINS
20 PINS
15 PINS
10 PINS

100 PINS TOTAL

2. MEASURE LONGITUDINAL AND HOOP STRESSES AT 72 SPOTS ON EACH PIN.

Fig. 1 Test Procedure

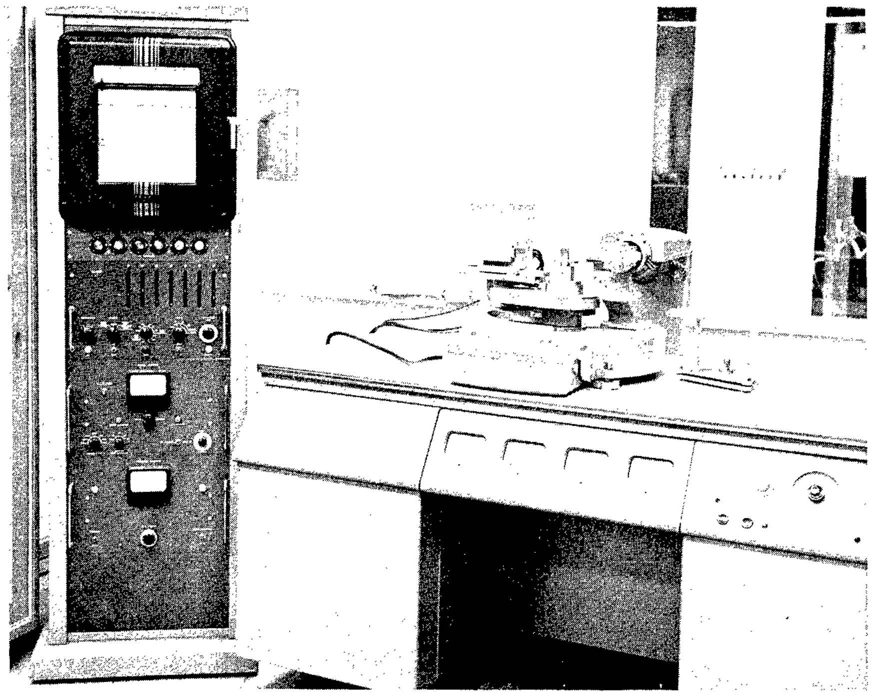


Fig. 2 General Electric x-ray diffraction unit model XRD-3

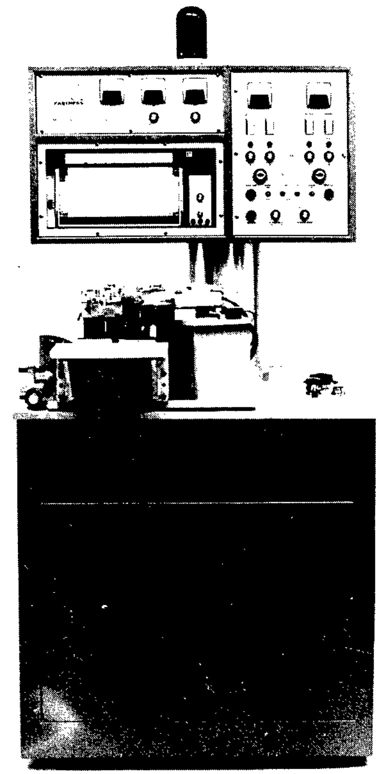


Fig. 3 Automated x-ray diffraction unit for rapid measurement of residual stress

CHART NO. 1

RESULTS

	RANGE OF RESULTS							
	LONGITUDINAL STRESS				HOOP STRESS			
	MEAN		STD. DEV.		MEAN		STD. DEV.	
	HI	LOW	HI	LOW	HI	LOW	HI	LOW
1. AFTER CORE HARDENING	+15	-8	6	2	+18	-12	6	3
2. AFTER STRAIGHTENING	+15	+5	33	20	+10	-9	6	3
3. AFTER INDUCTION HARDENING	-60	-98	14	4	-90	-119	23	7
4. AFTER STRAIGHTENING	-59	-88	15	4	-87	-119	20	5
5. AFTER CENTERLESS GRINDING	-30	-64	20	6	-2	-38	15	4
6. AFTER STRESS RELIEF	-28	-40	16	7	+1	-9	10	5
7. AFTER SHOT PEENING	-48	-63	7	4	-51	-66	8	4

CHART NO. 2

DATA ON TRACK PINS PROCESSED UP TO AND INCLUDING CORE HARDENING

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
1	1	+9.28	2.1	+5.97	3.5
2	1	+14.2	2.6	+12.3	3.4
3	1	+14.5	3.0	+17.9	3.6
4	1	+14	2	+16	6
5	1	−5	3	−4	4
6	1	+6	6	−7	4
7	1	−6	3	−11	5
8	1	−5	3	−10	5
9	1	−8	4	−12	4
10	1	−1	3	−5	4

UNITS : K psi

+ : TENSILE

- : COMPRESSIVE

CHART NO. 3

DATA ON TRACK PINS PROCESSED UP TO AND INCLUDING STRAIGHTENING (FIRST TIME)

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
1	2	+10	23	+1	4
2	2	+9	23	+2	4
3	2	+10	24	+2	5
4	2	+6	27	0	6
5	2	+9	21	+4	3
6	2	+11	27	+10	3
7	2	+11	27	+8	5
8	2	+15	26	+7	3
9	2	+15	25	+6	3
10	2	+5	2	+2	3

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
11	1	+11	32	+2	4
12	1	+11	33	+2	5
13	1	+10	24	+4	6
14	1	+10	25	+1	5
15	1	+7	23	-3	5
16	1	+11	24	+2	5
17	1	+8	24	-3	3
18	1	+5	25	-4	4
19	1	+6	20	-9	6
20	1	+12	25	-2	5

UNITS : K psi
+ : TENSILE
- : COMPRESSIVE

CHART NO. 4

DATA ON TRACK PINS PROCESSED UP TO AND INCLUDING INDUCTION HARDENING

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
11	2	-79	10	-101	23
12	2	-85	8	-100	15
13	2	-81	7	-91	21
14	2	-65	8	-92	14
15	2	-67	11	-54	8
16	2	-79	8	-64	23
17	2	-69	13	-56	39
18	2	-69	5	-73	14
19	2	-60	12	-61	18
20	2	-79	7	-77	12

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
21	1	-80	6	-99	10
22	1	-75	7	-90	22
23	1	-86	6	-91	17
24	1	-79	16	-92	23
25	1	-98	14	-105	7
26	1	-86	12	-94	11
27	1	-90	10	-111	22
28	1	-94	9	-119	17
29	1	-77	12	-108	18
30	1	-82	9	-105	21
31	1	-80	12	-107	19
32	1	-84	10	-107	7
33	1	-90	4	-109	8
34	1	-82	5	-105	8
35	1	-80	8	-101	9

UNITS : K psi
+ : TENSILE
- : COMPRESSIVE

CHART NO. 5

DATA ON TRACK PINS PROCESSED UP TO AND INCLUDING STRAIGHTENING (SECOND TIME)

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
21	2	-74	6	-79	9
22	2	-72	7	-75	20
23	2	-75	9	-76	17
24	2	-72	15	-78	18
25	2	-88	9	-87	11
26	2	-71	11	-79	7
27	2	-76	7		
28	2	-81	7		
29	2	-62	8		
30	2	-70	6		
31	2	-71	10		
32	2	-75	10		
33	2	-80	8		
34	2	-77	7		
35	2	-69	10		

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
36	1	-73	12	-95	19
37	1	-72	7	-87	12
38	1	-79	4	-87	14
39	1	-59	8	-93	15
40	1	-76	8	-117	8
41	1	-81	7	-102	9
42	1	-75	12	-101	12
43	1	-79	7	-108	9
44	1	-78	10	-112	11
45	1	-76	8	-111	11
46	1	-78	6	-93	16
47	1	-87	9	-94	18
48	1	-67	8	-108	9
49	1	-71	7	-119	11
50	1	-80	14	-98	10
51	1	-72	8	-107	13
52	1	-72	10	-102	15
53	1	-61	9	-94	20
54	1	-66	11	-98	8
55	1	-78	11	-104	5

UNITS : K psi
+ : TENSILE
- : COMPRESSIVE

CHART NO. 6

DATA ON TRACK PINS PROCESSED UP TO AND INCLUDING CENTERLESS GRINDING

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
36	2	-39	11	+4	7
37	2	-30	11	+10	9
38	2	-39	9	+1	7
39	2	-37	17	+1	9
40	2	-45	13	-3	7
41	2	-33	13	+5	8
42	2	-41	14	0	10
43	2	-31	16	-3	8
44	2				
45	2	-45	10	-7	7
46	2	-37	13	-9	9
47	2	-33	10	+7	6
48	2	-40	12	-2	6
49	2	-39	15	-2	11
50	2	-29	8	-3	7
51	2	-43	11	+3	7
52	2	-28	12	+4	9
53	2	-29	10	+6	7
54	2				
55	2				

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
56	1	-64	16	-38	13
57	1	-50	13	-23	12
58	1	-43	7	-10	4
59	1	-41	9	-8	7
60	1	-48	7	-10	6
61	1	-49	16	-18	12
62	1	-57	10	-22	7
63	1	-52	6	-18	4
64	1	-45	14	-19	9
65	1	-36	9	-4	7
66	1	-43	15	-2	12
67	1	-44	16	-3	10
68	1	-39	16	-4	10
69	1	-45	13	-6	10
70	1	-42	20	-8	15
71	1	-34	9	-6	8
72	1	-37	9	-2	7
73	1	-38	11	-4	8
74	1	-34	13	-6	9
75	1	-39	15	-8	13

UNITS : K psi
+ : TENSILE
- : COMPRESSIVE

CHART NO. 7

DATA ON TRACK PINS PROCESSED UP TO AND INCLUDING STRESS RELIEF

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
56	2	-30	12	+6	9
57	2	-52	10	+10	8
58	2	-43	6	-12	4
59	2	-49	7	-15	5
60	2	-53	5	-12	5
61	2	-51	12	-11	6
62	2	-57	7	-20	7
63	2	-55	5	-26	6
64	2				
65	2				
66	2				
67	2				
68	2				
69	2				
70	2				
71	2				
72	2				
73	2				
74	2				
75	2				

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
76	1	-40	11	-9	6
77	1	-35	11	-9	7
78	1	-30	16	-5	10
79	1	-34	9	-3	5
80	1	-35	10	-9	8
81	1	-36	14	-5	10
82	1	-28	10	-2	8
83	1	-32	14	-5	9
84	1	-34	14	-9	10
85	1	-29	8	-4	7
86	1	-37	10	-9	5
87	1	-37	8	-3	7
88	1	-35	7	-4	7
89	1	-33	7	-1	6
90	1	-31	11	+0.7	9

UNITS : K psi
+ : TENSILE
- : COMPRESSIVE

CHART NO. 8

DATA ON TRACK PINS PROCESSED UP TO AND INCLUDING SHOT PEENING

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
76	2	-58	10	-65	7
77	2	-65	8	-80	5
78	2	-66	8	-62	6
79	2	-63	7	-62	8
80	2	-57	7	-65	5
81	2	-56	10	-59	11
82	2	-55	7	-58	5
83	2	-59	11		
84	2				
85	2				
86	2				
87	2				
88	2				
89	2				
90	2				

TRACK PIN NO.	PHASE	MEAN LONGITUDINAL STRESS	STD. DEVIATION (LONGITUDINAL)	MEAN HOOP STRESS	STD. DEVIATION (HOOP)
91	1	-57	6	-56	5
92	1	-48	6	-58	8
93	1	-60	5	-51	5
94	1	-57	5	-55	5
95	1	-62	6	-62	5
96	1	-52	6	-57	6
97	1	-63	6	-57	5
98	1	-57	7	-59	6
99	1	-54	6		
100	1	-59	4	-66	44

UNITS : K psi
+ : TENSILE
- : COMPRESSIVE

CHART NO. 9

DATA ON TRACK PIN NO. 75
(PHASE I)
LONGITUDINAL STRESSES

	1	2	3	4	5	6	7	8	9
A	-70	-69	-54	-58	-52	-54	-53	-40	-48
B	-50	-60	-55	-60	-54	-52	-50	-47	-55
C	-29	-32	-32	-30	-38	-24	-41	-36	-52
D	-9	-26	-30	-17	-27	-21	-26	-36	-44
E	-15	-12	-27	-9	-20	-22	-22	-33	-35
F	-28	-31	-20	-6	-22	-14	-20	-35	-37
G	-60	-50	-54	-52	-40	-42	-32	-37	-36
H	-55	-51	-55	-54	-50	-44	-45	-42	-40

UNITS : K psi
+ : TENSILE
- : COMPRESSIVE

MEAN -38.5833
STD. DEV. 15.2738

CHART NO. 10

DATA ON TRACK PIN NO. 75
(PHASE I)
HOOP STRESSES

	1	2	3	4	5	6	7	8	9
A	-42	-34	-22	-23	-22	-25	-17	-2	-5
B	-22	-25	-21	-26	-27	-28	-22	-11	-12
C	-6	-2	+6	-3	-11	+6	-12	-5	-14
D	+18	+10	-3	-6	-7	-2	-4	-5	-7
E	+17	+8	-6	+18	-5	0	+9	+3	-2
F	+4	+2	+8	+8	+3	+5	-5	0	+3
G	-20	-17	-20	-17	-10	-8	-4	-4	0
H	-24	-20	-22	-16	-17	-8	-12	-4	0

UNITS : K psi
+ : TENSILE
- : COMPRESSIVE

MEAN -8.1389
STD. DEV. 12.5309

CHART NO. 11

DATA ON TRACK PIN NO. 85
(PHASE I)
LONGITUDINAL STRESSES

	1	2	3	4	5	6	7	8	9
A	-42	-43	-41	-44	-36	-32	-35	-26	-27
B	-32	-30	-42	-42	-33	-33	-39	-25	-29
C	-28	-18	-31	-33	-31	-36	-24	-33	-29
D	-12	-31	-30	-21	-20	-16	-33	-32	-22
E	-7	-18	-16	-16	-26	-10	-25	-33	-31
F	-23	-17	-25	-29	-26	-27	-33	-33	-35
G	-22	-30	-32	-35	-35	-20	-49	-36	-25
H	-36	-31	-42	-35	-32	-27	-25	-36	-29

UNITS : K psi
+ : TENSILE
- : COMPRESSIVE

MEAN -29.4167
STD. DEV. 8.2918

CHART NO. 12

DATA ON TRACK PIN NO. 85
(PHASE I)
HOOP STRESSES

	1	2	3	4	5	6	7	8	9
A	-8	-7	-10	-8	-6	-8	-8	-4	-10
B	-8	-8	-5	-3	-4	-7	-6	-10	-6
C	-8	-10	-11	-6	-12	-14	-10	-17	-9
D	+6	-3	-6	0	+4	-2	-12	-4	-8
E	+5	+4	+14	+10	+3	+20	+3	-8	-9
F	+4	0	+8	+4	+3	+2	-2	+3	-6
G	-1	-10	+4	-7	-2	+3	-4	-2	-4
H	-7	-6	-6	-12	-17	-8	-6	-6	-2

UNITS : K psi
+ : TENSILE
- : COMPRESSIVE

MEAN -3.8750
STD. DEV. 6.8153

CHART NO. 13

DATA ON TRACK PIN NO. 95
(PHASE I)
LONGITUDINAL STRESSES

	1	2	3	4	5	6	7	8	9
A	-60	-63	-66	-60	-60	-64	-62	-61	-54
B	-65	-59	-53	-56	-63	-57	-61	-62	-59
C	-56	-62	-48	-52	-59	-61	-54	-61	-61
D	-73	-68	-65	-60	-55	-58	-61	-64	-66
E	-67	-68	-70	-69	-80	-64	-77	-80	-69
F	-61	-61	-64	-58	-63	-65	-65	-72	-73
G	-57	-63	-60	-51	-53	-55	-56	-55	-56
H	-60	-66	-64	-60	-66	-72	-61	-63	-64

UNITS : K psi
\+ : TENSILE
\- : COMPRESSIVE

MEAN -62.1806
STD. DEV. 6.3297

CHART NO. 14

DATA ON TRACK PIN NO. 95
(PHASE I)
HOOP STRESSES

	1	2	3	4	5	6	7	8	9
A	-60	-64	-64	-50	-62	-64	-63	-66	-61
B	-66	-54	-53	-50	-65	-70	-62	-65	-63
C	-54	-62	-59	-63	-58	-62	-57	-63	-55
D	-70	-68	-59	-62	-64	-62	-58	-66	-64
E	-72	-66	-70	-60	-70	-62	-74	-78	-64
F	-64	-54	-67	-60	-62	-62	-63	-75	-71
G	-58	-60	-60	-58	-57	-63	-58	-56	-56
H	-62	-60	-58	-58	-58	-62	-60	-64	-64

UNITS : K psi
\+ : TENSILE
\- : COMPRESSIVE

MEAN -62.1389
STD. DEV. 5.4341

CHART NO. 15

STATISTICAL DISTRIBUTION OF DATA FOR TRACK PIN NO. 75

N = 72
MEAN = -38.6528
STD. DEV. = 15.4292
SKEWNESS = 0.1072
KURTOSIS = 2.2432

CELL #	LOWER LIMIT	NO. OF OBS	% RELATIVE FREQ
1	-100.0000	0	0.00000
2	-90.0000	0	0.00000
3	-80.0000	1	1.38889
4	-70.0000	1	1.38889
5	-60.0000	19	26.38889
6	-50.0000	12	16.66667
7	-40.0000	16	22.22222
8	-30.0000	13	18.05556
9	-20.0000	7	9.72222
10	-10.0000	3	4.16667

LONGITUDINAL STRESS

N = 72
MEAN = -8.1389
STD. DEV. = 12.5309
SKEWNESS = -0.1654
KURTOSIS = 2.6289

CELL #	LOWER LIMIT	NO. OF OBS	% RELATIVE FREQ
1	-100.0000	0	0.00000
2	-90.0000	0	0.00000
3	-80.0000	0	0.00000
4	-70.0000	0	0.00000
5	-60.0000	0	0.00000
6	-50.0000	1	1.38889
7	-40.0000	1	1.38889
8	-30.0000	13	18.05556
9	-20.0000	14	19.44444
10	-10.0000	23	31.94444
11	0.0000	16	22.22222
12	10.0000	4	5.55556

HOOP STRESS

CHART NO. 16

STATISTICAL DISTRIBUTION OF DATA FOR TRACK PIN NO. 85

N = 72
MEAN = -29.4167
STD. DEV. = 8.2918
SKEWNESS = 0.3365
KURTOSIS = 3.0624

CELL #	LOWER LIMIT	NO. OF OBS	% RELATIVE FREQ
1	-100.0000	0	0.00000
2	-90.0000	0	0.00000
3	-80.0000	0	0.00000
4	-70.0000	0	0.00000
5	-60.0000	0	0.00000
6	-50.0000	8	11.11111
7	-40.0000	29	40.27778
8	-30.0000	24	33.33333
9	-20.0000	9	12.50000
10	-10.0000	2	2.77778

LONGITUDINAL STRESS

N = 72
MEAN = -3.8750
STD. DEV. = 6.8153
SKEWNESS = 0.8717
KURTOSIS = 4.0675

CELL #	LOWER LIMIT	NO. OF OBS	% RELATIVE FREQ
1	-100.0000	0	0.00000
2	-90.0000	0	0.00000
3	-80.0000	0	0.00000
4	-70.0000	0	0.00000
5	-60.0000	0	0.00000
6	-50.0000	0	0.00000
7	-40.0000	0	0.00000
8	-30.0000	0	0.00000
9	-20.0000	7	9.72222
10	-10.0000	45	62.50000
11	0.0000	17	23.61111
12	10.0000	2	2.77778
13	20.0000	1	1.38889

HOOP STRESS

CHART NO. 17

STATISTICAL DISTRIBUTION OF DATA FOR TRACK PIN NO. 95

N = 72
MEAN = -62.1806
STD. DEV. = 6.3297
SKEWNESS = -0.5673
KURTOSIS = 3.5843

CELL #	LOWER LIMIT	NO. OF OBS	% RELATIVE FREQ
1	-100.0000	0	0.00000
2	-90.0000	0	0.00000
3	-80.0000	7	9.72222
4	-70.0000	37	51.38889
5	-60.0000	27	37.50000
6	-50.0000	1	1.38889

LONGITUDINAL STRESS

N = 72
MEAN = -62.1389
STD. DEV. = 5.4341
SKEWNESS = -0.3708
KURTOSIS = 3.4610

CELL #	LOWER LIMIT	NO. OF OBS	% RELATIVE FREQ
1	-100.0000	0	0.00000
2	-90.0000	0	0.00000
3	-80.0000	5	6.94444
4	-70.0000	39	54.16667
5	-60.0000	26	36.11111
6	-50.0000	2	2.77778

HOOP STRESS

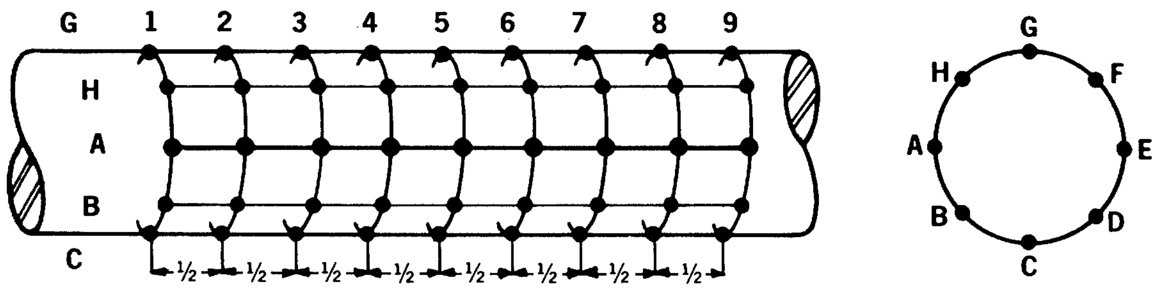


Fig. 4 Location of data points on central section of track pin

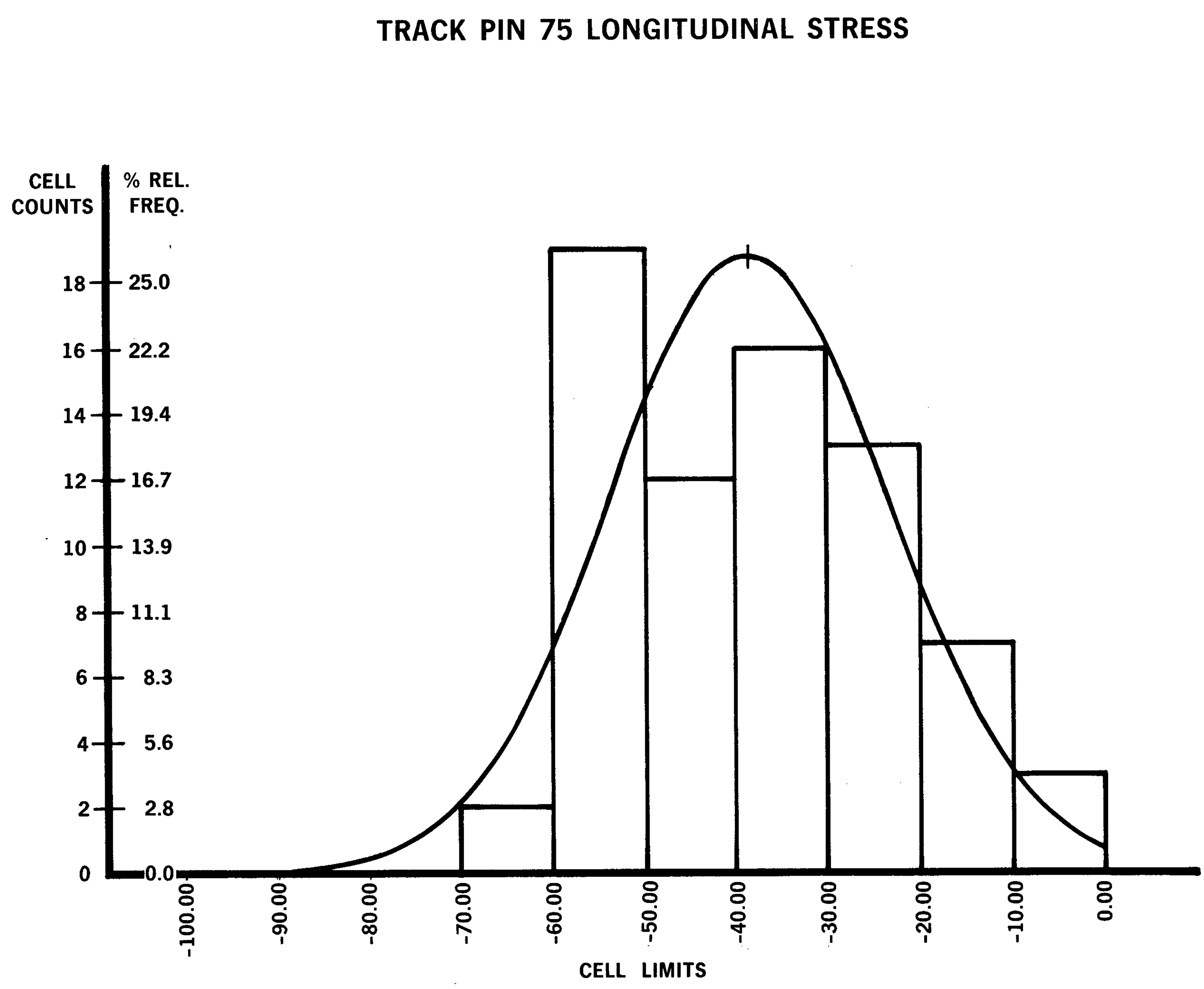


Fig. 5(a) Histogram for phase 1 data on track pin no. 75 (longitudinal stress)

TRACK PIN 75 HOOP STRESS

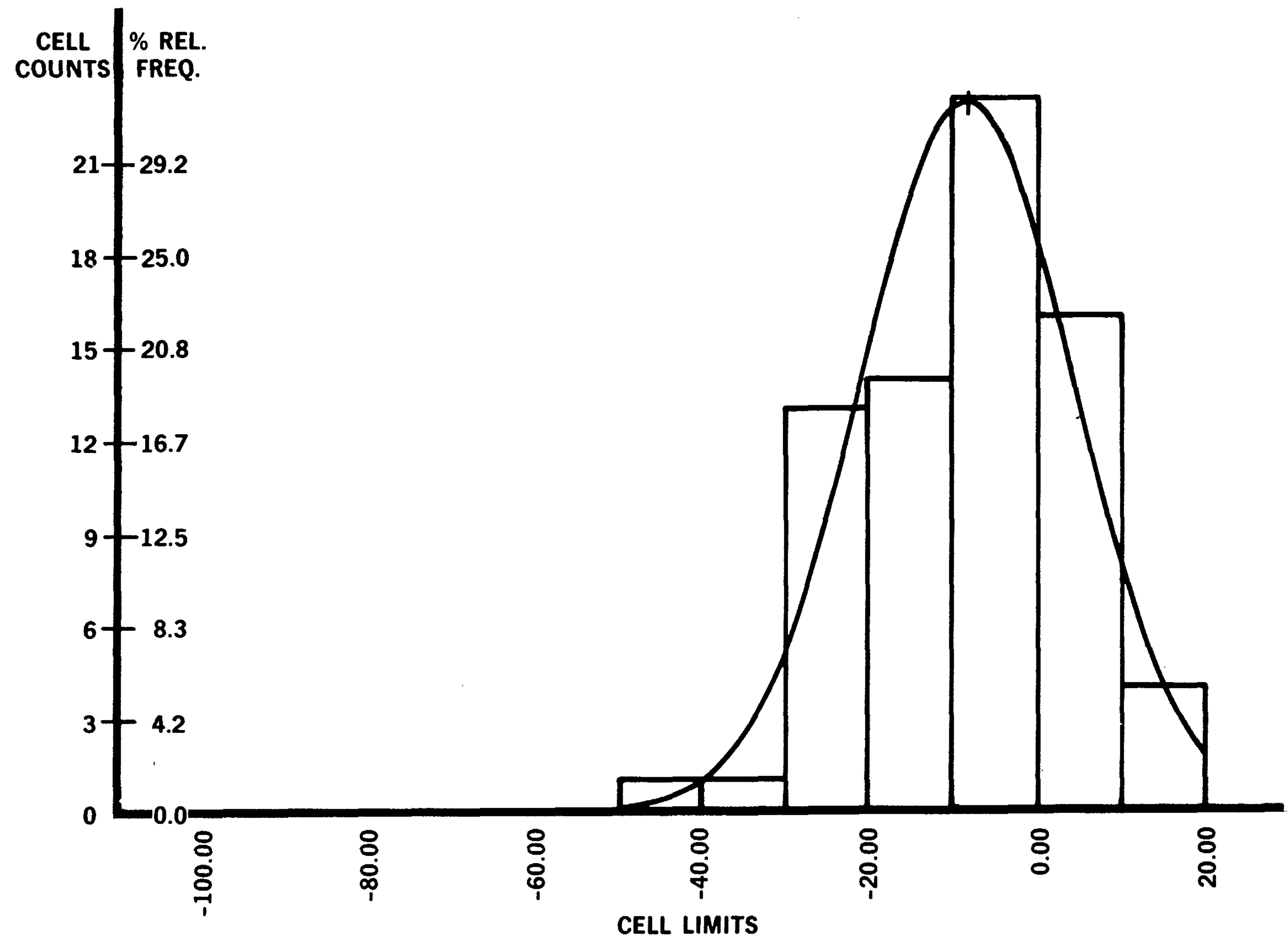


Fig. 5(b) Histogram for phase 1 data on track pin no. 75 (hoop stress)

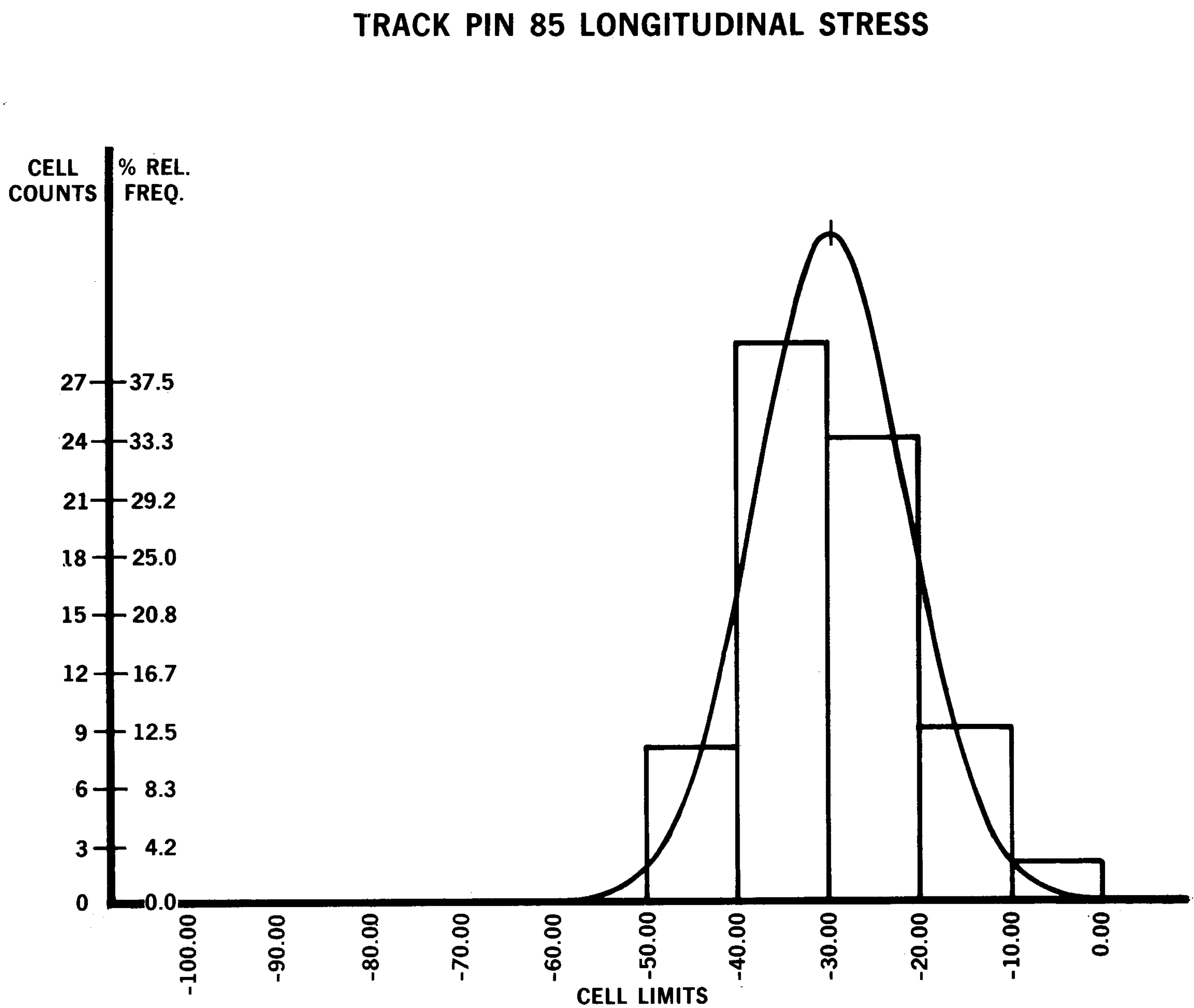


Fig. 6(a) Histogram for phase 1 data on track pin no. 85 (longitudinal stress)

TRACK PIN 85 HOOP STRESS

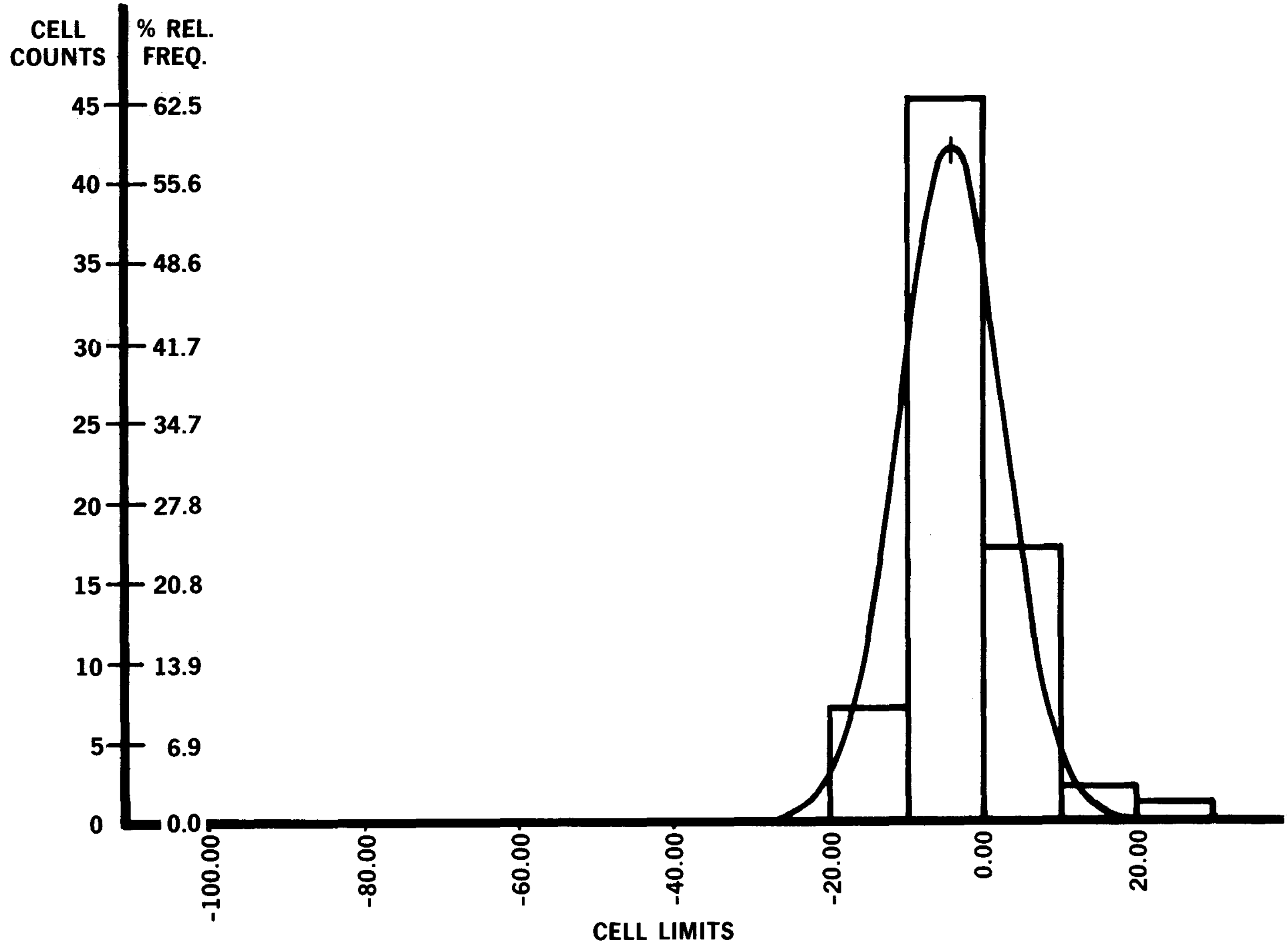


Fig. 6(b) Histogram for phase 1 data on track pin no. 85 (hoop stress)

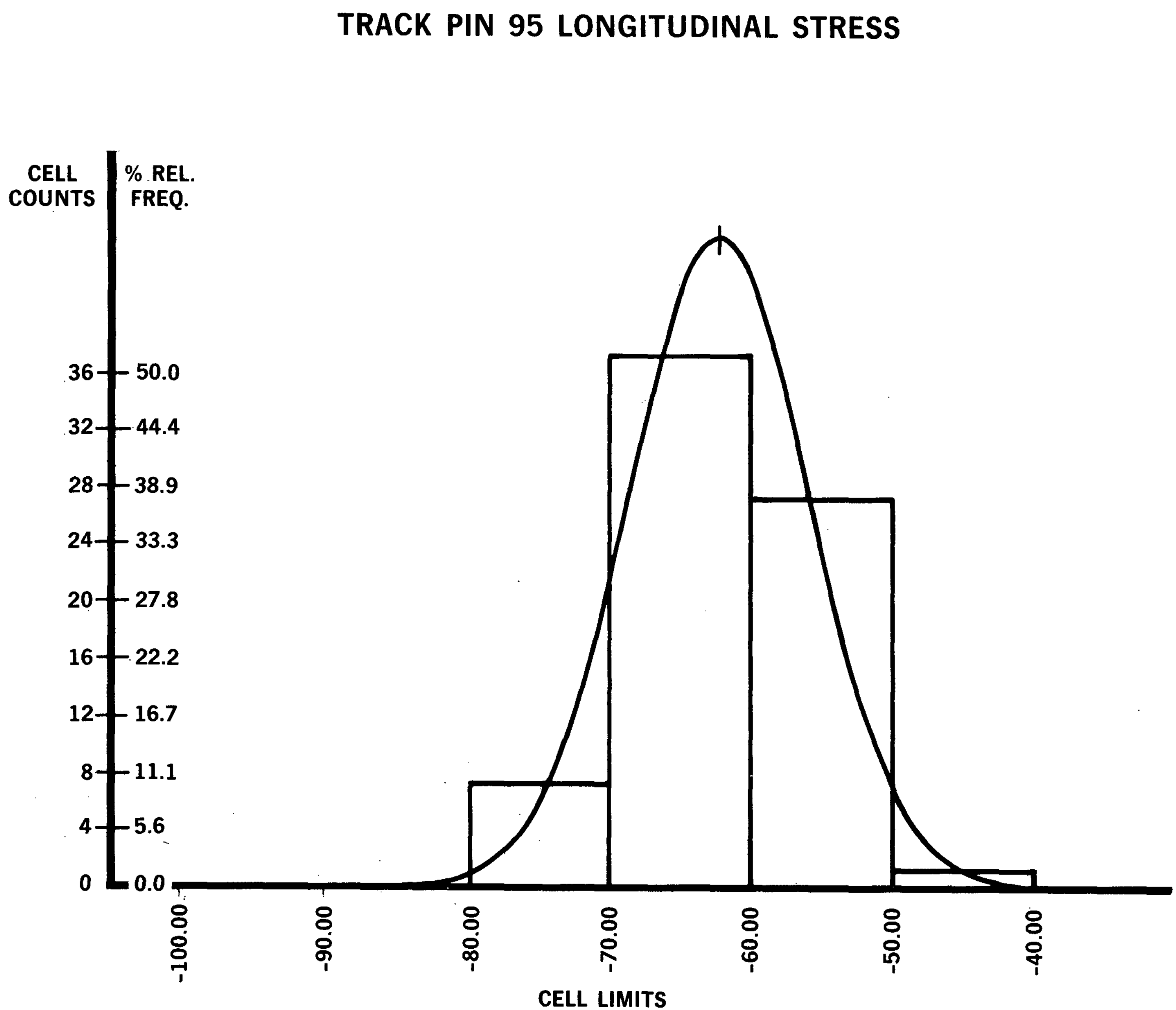


Fig. 7(a) Histogram for phase 1 data on track pin no. 95 (longitudinal stress)

TRACK PIN 95 HOOP STRESS

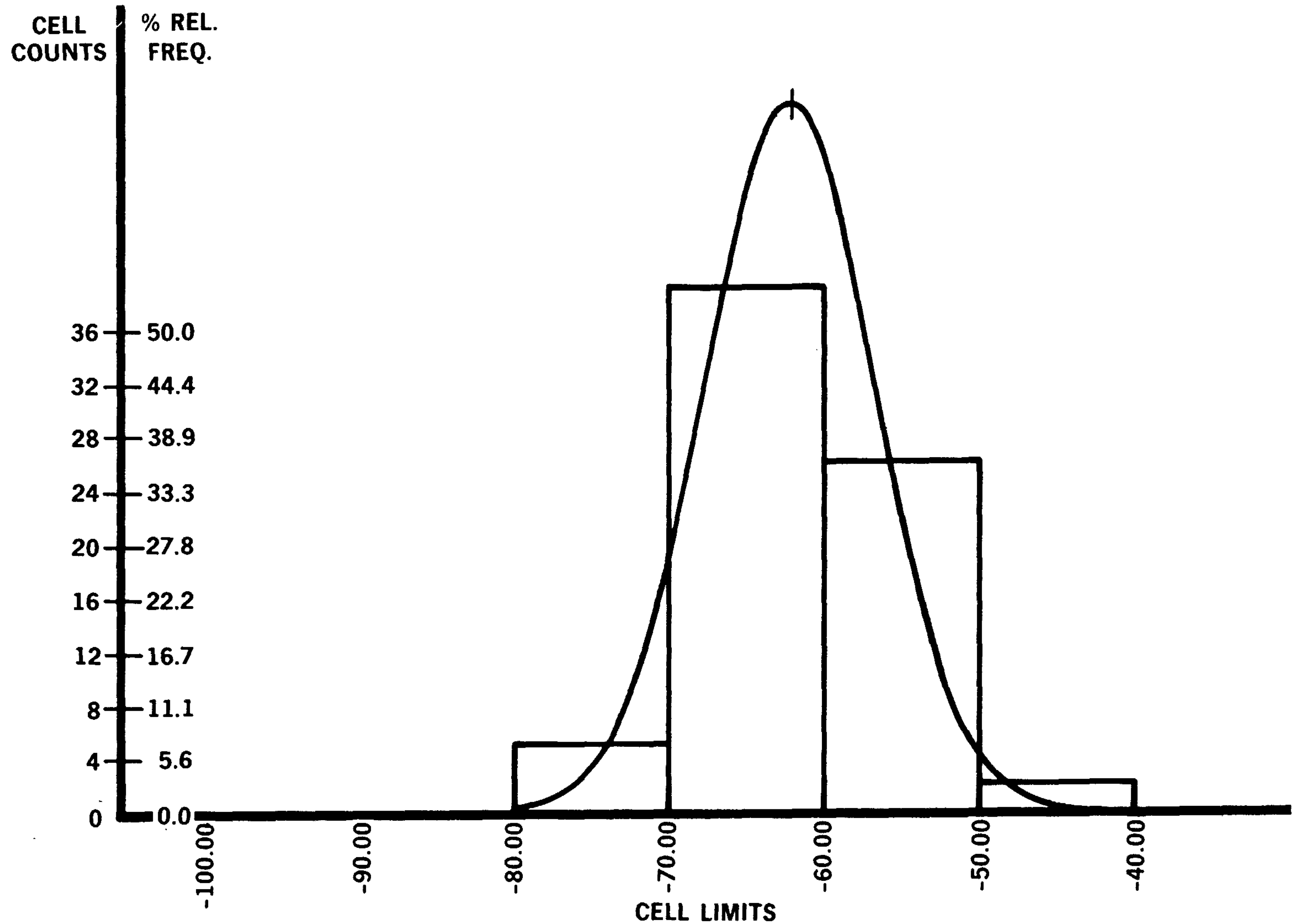


Fig. 7(b) Histogram for phase 1 data on track pin no. 95 (hoop stress)

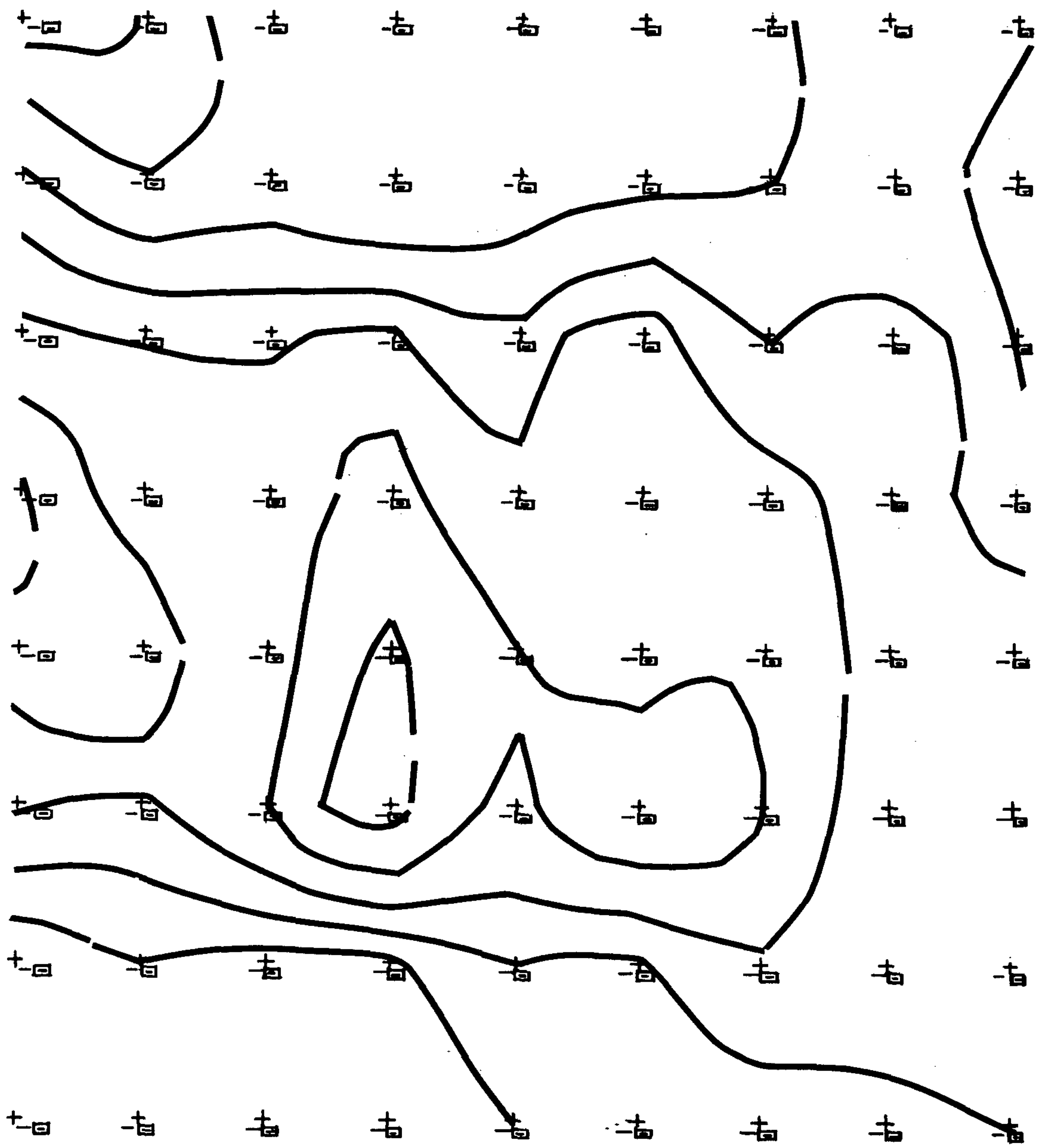


Fig. 8 (a) Isostress plot for phase 1 data on track pin no. 75 (longitudinal stress)

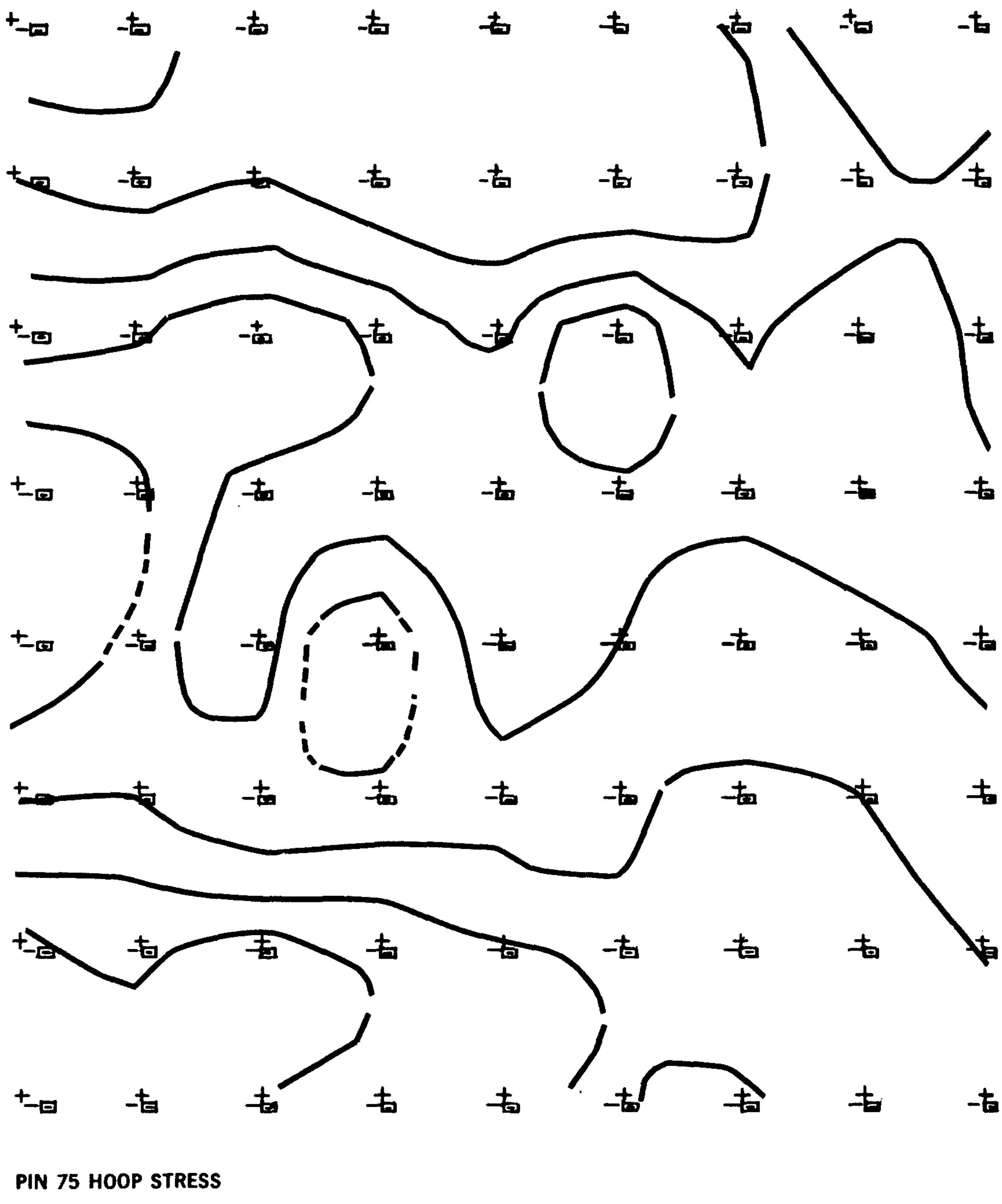


Fig. 8 (b) Isostress plot for phase 1 data on track pin no. 75 (hoop stress)

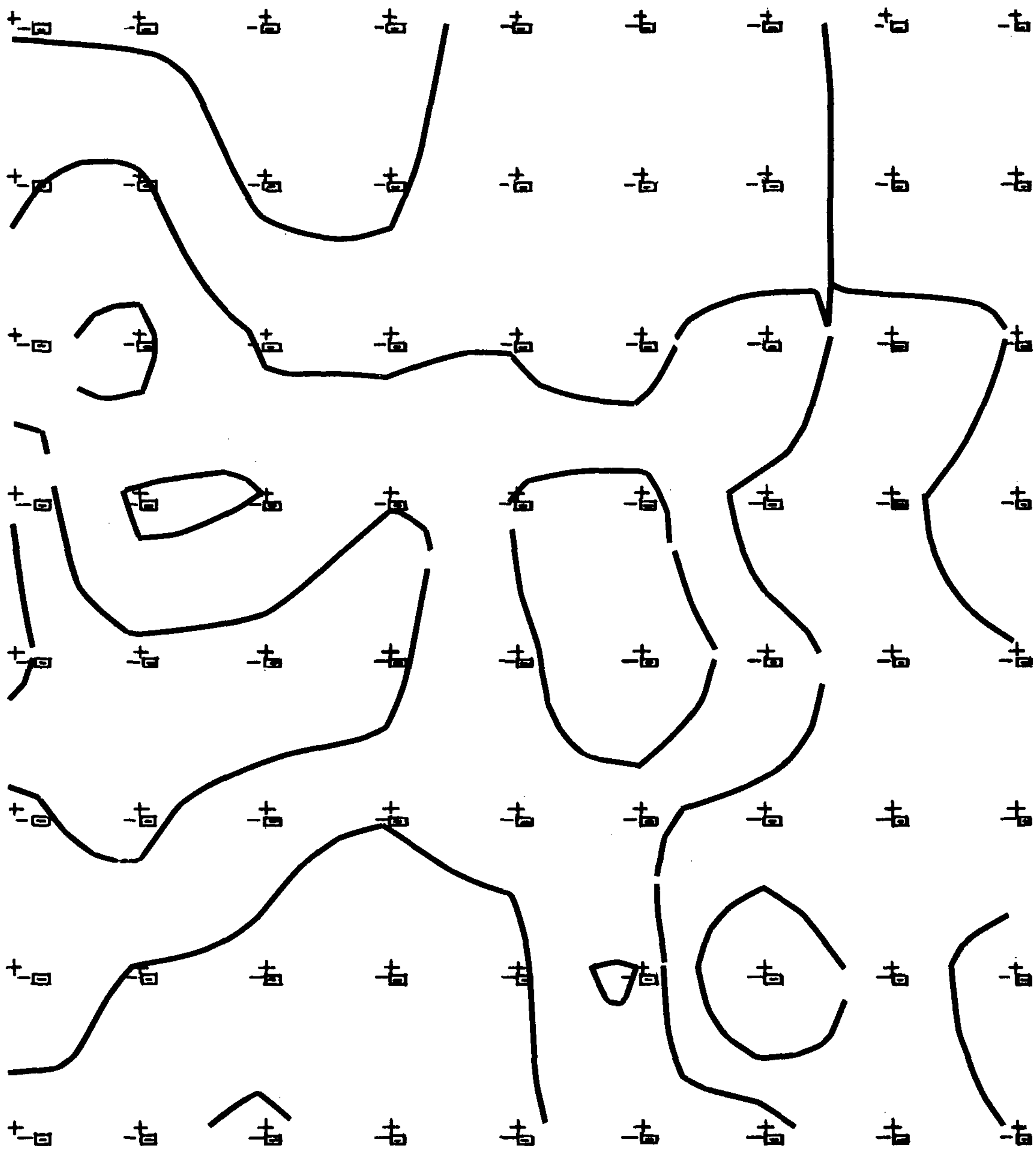
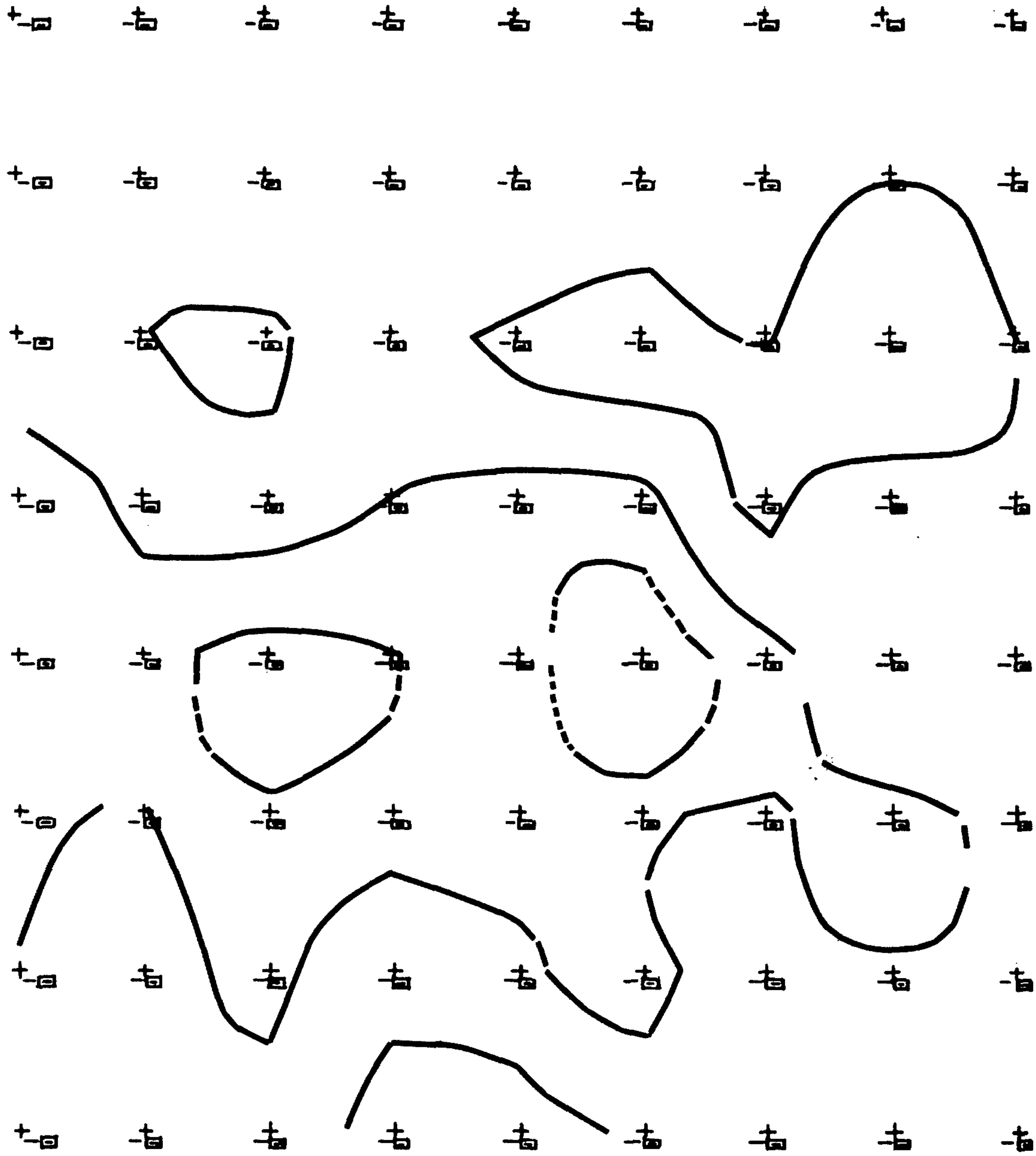


Fig. 9 (a) Isostress plot for phase 1 data on track pin no. 85 (longitudinal stress)



PIN 85 HOOP STRESS

Fig. 9 (b) Isostress plot for phase 1 data on track pin no. 85 (hoop stress)

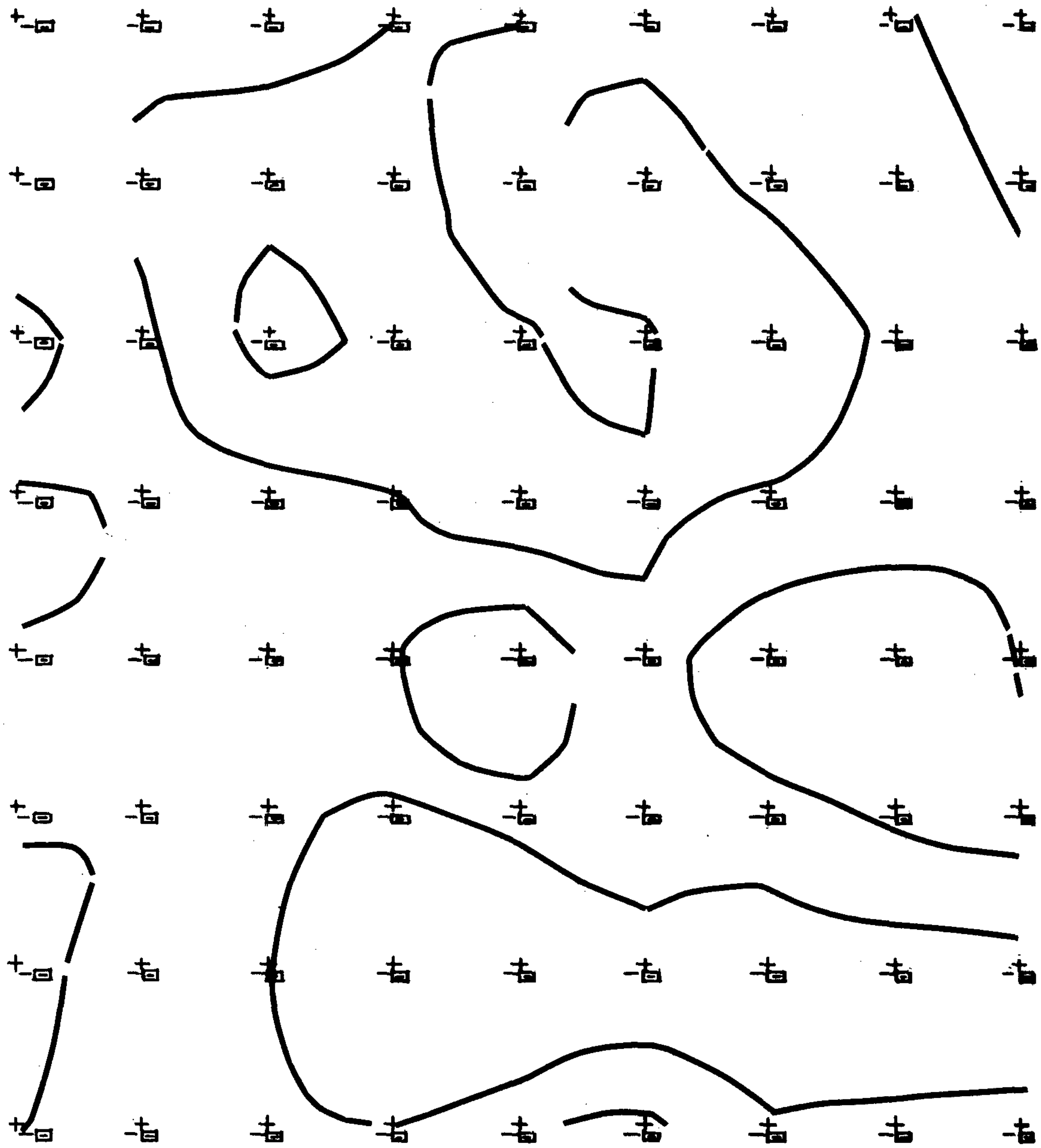
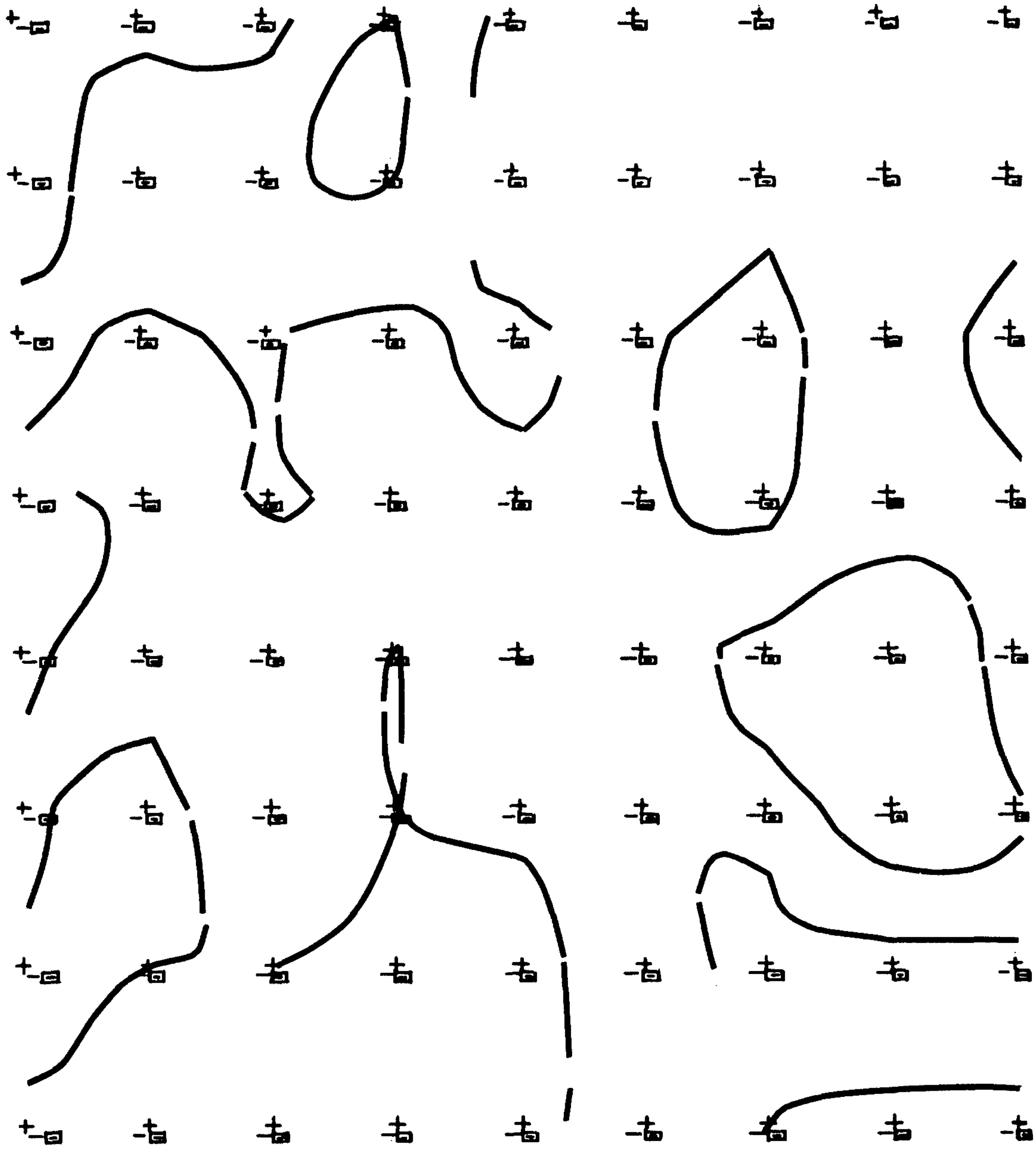


Fig. 10 (a) Isostress plot for phase 1 data on track pin no. 95 (longitudinal stress)



PIN 95 HOOP STRESS

Fig. 10 (b) Isostress plot for phase 1 data on track pin no. 95 (hoop stress)

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